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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 :
B32B 3/02, 5/16, 9/00
H01F 1/00, G11B 5/66, 5/02

A1

(11) International Publication Number: WO 93/12928

(43) International Publication Date: 8 July 1993 (08.07.93)

(21) International Application Number: PCT/US92/10485

(22) International Filing Date: 7 December 1992 (07.12.92)

(30) Priority data:
07/817,282 3 January 1992 (03.01.92) US

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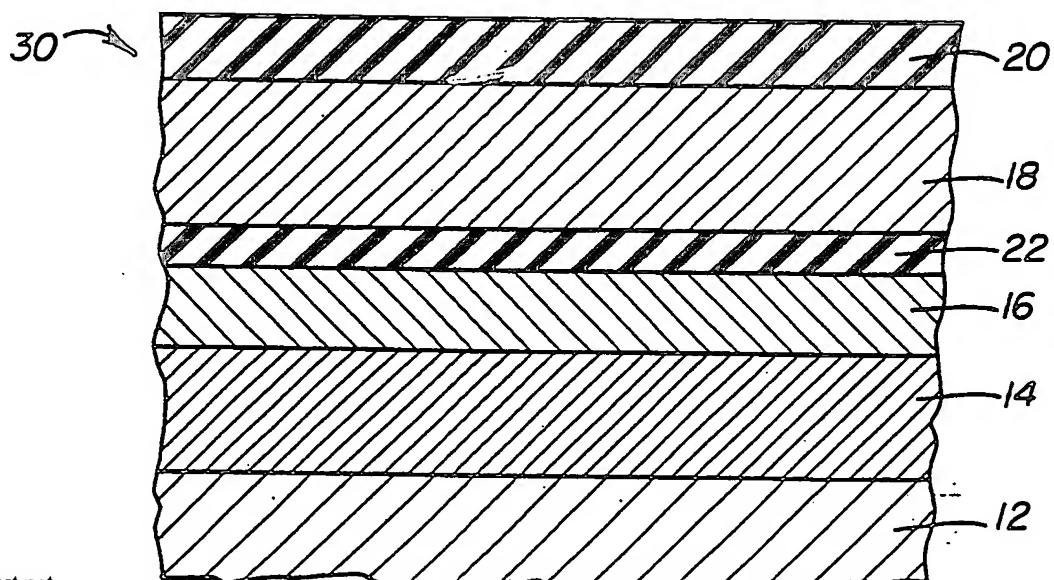
(81) Designated States: JP, KR, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: MAGNETIC RECORDING MEDIA EMPLOYING SOFT MAGNETIC MATERIAL



(57) Abstract

A magnetic recording medium employing a thin layer of nonmagnetic material (22) separating a soft magnetic layer (18) and a relatively thicker magnetic recording layer (16) is disclosed. The magnetic recording medium may incorporate conventional magnetic recording materials with the thin nonmagnetic layer (22) being silicon, chromium or carbon. The magnetic recording medium may be prepared by sputtering or other vapor deposition methods. A method for preparing a magnetic recording medium according to the present invention deposits the magnetic recording layer (16) either directly on a substrate (12), or, optionally, on a nucleating layer (14). The thin nonmagnetic layer (22) separates the magnetic recording layer (16) from the soft magnetic layer (18). A protective layer (20) overlies the soft magnetic layer (18). The deposition is achieved under conditions that maintain integrity of the magnetic recording layer.

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MAGNETIC RECORDING MEDIA EMPLOYING SOFT MAGNETIC MATERIAL

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to magnetic recording media, and more specifically, to multilayered horizontal recording media incorporating a highly magnetically permeable material.

Description of the Related Art

Conventional recording media include magnetic recording disks, tapes and "floppy" disks and typically have a multiple layer configuration. The base of a magnetic recording medium is a substrate, commonly a nickel-phosphorus-plated aluminum disk or thermoplastic tape or film, mechanically supporting one or more layers of magnetic material. Finally, a protective layer may be provided to prevent abrasion of the magnetic material by the magnetic head, or corrosion.

Data is stored magnetically on recording media by creating, with a magnetic head and a current, a pattern of magnetization zones within the magnetic layer. Zone boundaries, defined by magnetic flux reversals within the magnetic layer, represent the data. The amount of data stored therefore depends in great part on the ability of

the magnetic material to support distinct, closely spaced flux reversals.

Magnetic materials may be characterized according to the orientation of the easy axis of magnetization. This orientation is the direction within the crystalline structure of the magnetic material that minimizes the energy density associated with the orientation of magnetic dipoles in the magnetic layer. For vertical recording media, the easy axis of magnetization is perpendicular to the surface of the layer of magnetic material. For horizontal recording media, the easy axis of magnetization is parallel to the surface of the magnetic layer. Horizontal recording media currently in use in conventional disk drives typically achieve linear bit densities on the order of 45,000 flux changes per inch (45 kfci).

Vertical recording materials promise even higher density recording since theoretically more data may be packed in a pattern of magnetization zones perpendicular to the surface of the magnetic recording layer as opposed to in the plane of the layer, as in horizontal recording media. However, because of difficulties in the commercial development of productive magnetic recording disks incorporating vertical recording materials, horizontal recording materials remain of great commercial significance.

Selection of a suitable magnetic material may be aided by reference to the hysteresis or "BH" loop for the material produced by an applied magnetic field, H. For example, the degree of magnetization induced in a magnetic material and the corresponding signal strength of data stored therein can be increased by using as the magnetic recording film a material with a greater magnetic moment. In a given magnetic recording disk, therefore, a relatively thinner layer of a magnetic

material with a relatively higher moment can provide a signal of the same strength as a thicker layer of a magnetic material with a relatively lower magnetic moment. Other benefits realized by use of the higher moment material include more uniform magnetic field strength detected by the head and more sharply defined magnetic transitions, allowing a higher recorded data density.

The squareness of a magnetic recording material, the ratio of remanent magnetization to magnetic saturation indirectly measures the potential magnitude of a signal retained in a magnetic material once the applied magnetic field is reduced or removed.

Another important feature of a magnetic material depicted in its BH loop is coercivity, H_c. Where H_c is greater than several hundred Oersted (Oe), the magnetic material is considered "hard", like cobalt alloys and some oxides of chromium and iron. These materials tend to retain induced magnetization making them suitable for magnetic recording materials. For a "soft" magnetic material like some nickel-iron alloys, H_c is on the order of a few Oe. Such materials are advantageously used in magnetic heads because they are easily remagnetized with relatively low magnetic fields. The coercivity measures the field necessary to demagnetize a magnetic material and is desirably of such a magnitude that data may be overwritten relatively easily while avoiding spontaneous erasure upon encountering a stray magnetic flux.

The manufacturing process also plays a significant role in determining the properties of a magnetic recording medium. For example, substrate surface treatments, such as texturization of disks, and the method and parameters of the deposition of the magnetic layers are often critical to the development of

microscopic structures that permit and enhance magnetic recording properties.

The desirability of achieving high performance magnetic recording media, particularly those relying on vertical recording films, and the accompanying reduction in cost of magnetic signal processing devices that such an achievement could bring, has spurred further research into their development. One area of research has focused on the utilization of soft magnetic materials in order to enhance the magnetic recording properties of vertical media. For example, U.S. Patents No. 4,717,592 and 4,657,819 describe two-film vertical recording media incorporating films of a soft magnetic material like a nickel-iron (NiFe) alloy, for example, sold under the trade name PERMALLOY™. In the former patent, two NiFe layers of different thicknesses are deposited on either side of a thermoplastic film substrate to suppress outgassing from and thermal degradation of the film before deposition of the vertical recording layer. The latter patent describes the adjustment of the composition of a NiFe layer (3000Å - 10,000Å), underlying a vertical recording layer, in order to reduce magnetic anisotropy-induced signal fluctuations.

United States Patent No. 5,041,922 (the '922 patent) and a related technical paper entitled "A High Resolution Flying Magnetic Disk Recording System with Zero Reproduce Spacing Loss", presented at the June 1991 IEEE Intermagnetics Conference, describe the use of a 700Å NiFe layer as a 'keeper'. These publications describe a configuration of a magnetic recording medium having a NiFe layer sputtered directly onto a magnetic layer. In the '922 patent, the 700Å NiFe lies above a 1000 Oe electroless cobalt-phosphorus magnetic film reportedly to effectively eliminate the losses in output signal due to the physical space or air gap between the head and the

medium during the read process. Specifically, reduction in spacing and reproduce gap losses is specifically attributed to the direct contact required between the NiFe and the magnetic recording layers. As a consequence, the magnetic flux from the data stored in the directly underlying magnetic film is retained or 'keepered' by the overlying NiFe layer. No flux is detected by the head and therefore, no signal is read. However, the paper states that when a bias is applied to the head, regions of the NiFe layer beneath the head become saturated. This saturation lowers the permeability of these regions. As a result, the flux readily permeates the saturated NiFe regions and a flux-induced signal is directed to the head through the unsaturated regions of the NiFe layer and through a conventional air gap between the disk and the head, where the resultant signal is detected.

As described in these publications, an advantage is obtained by the simple alteration of the structure of a conventional magnetic recording medium. That is, by the deposition of a soft magnetic layer directly on a magnetic recording layer and application of a saturating bias flux, spacing and reproduce gap losses can be reduced sufficiently to allow increased data densities without reducing the actual head flying height or requiring a head with a narrower gap.

Commercial utility of a magnetic recording disk requires cooperation of the magnetic recording material used in the disk with the head and other disk drive electronics, particularly with respect to achievement of high data resolution. Resolution depends in great part on minimizing levels of intersymbol interference.

To this end, research into the improvement of the interaction between the head and the magnetic material has also focused on the configuration of the head. As

described above, the configuration of the head with respect to the magnetic recording disk impacts the strength of the readback signal. In particular, the physical separation between the flying head and the surface of the disk contributes to losses in the output signal. For example, "spacing loss" results from the decreasing contribution of flux from a particular bit to the output signal detected by the head as the separation increases.

The configuration of the head itself plays an important role in the successful reproduction of the signal representing previously recorded data. In thin film (TF) or finite pole heads used in hard disk drives, for example, one source of loss in output signal is due to finite pole effects. These effects come into play as the head sweeps across a particular magnetic transition in order to read it. During this motion, the edges of the head poles can sense signals from adjacent magnetic transitions, interfering with the signal from the magnetic transition or "bit" intended to be read. This loss in output signal tends to recur periodically as the size of the magnetic transitions decreases, that is, as the data density increases. Therefore, instead of a smooth curve representing the decreasing output signal with increasing data density, the curve manifests "head bumps" where the length of the magnetic transitions approximates that of the pole thickness. Expensive solutions, e.g., the dedication of significant drive electronics, such as by the addition of filters, have been used to reduce finite pole effects. With the increasing use of TF heads in present and future disk drives and the push toward higher data densities, the loss in output signal due to finite pole effects represents a significant problem.

Gap length or gap "null" effects also cause significant loss of signal. When the length of two magnetic transitions representing adjacent bits of data approaches the length of the gap length between the head poles, the poles may not effectively discern between the signals representing each bit. Instead, upon playback, the signal from one bit almost cancels that from the adjacent bit because of the combined effects of their constructive and destructive phase interferences. As a result, the output signal is virtually eliminated, producing nulls at these points as the data density increases, contributing to an increased error rate for the drive.

Spacing losses and losses due to gap null effects represent the two largest limitations to achievement of higher density recording. While some improvement in signal quality may be obtained by improving the magnetic recording characteristics of the magnetic recording medium itself, as suggested by the above discussion, by far the greatest potential for improved recording performance lies in reducing spacing losses.

The magnitude of spacing loss with reference to magnetic tape recording performance was first described by the equation: spacing loss = $55 \cdot d/\lambda$, where d is the distance between the head and the medium and λ is the recording signal wavelength. This equation has been used as a basis for predicting spacing losses for other magnetic recording media such as floppy and "hard" disks.

SUMMARY OF THE INVENTION

A general purpose of the present invention is to provide a magnetic recording medium that has improved magnetic recording properties.

This purpose is achieved by the present invention through provision of a magnetic recording medium

invention including a substrate, a magnetic recording layer overlying the substrate, a nonmagnetic layer directly overlying the magnetic recording layer and a soft magnetic layer overlying the nonmagnetic layer. In a preferred embodiment, the nonmagnetic layer is deposited between the magnetic recording and soft magnetic layers such that upon application of a saturating bias flux, flux lines from the data stored in a particular bit, otherwise retained by the layer of soft magnetic material above the bit in the form of a closed path, open up to 'leak' along the layer of soft magnetic material and toward the head. Flux lines from all other bits remain keepered. The leaking flux couples with the head even at significant distances relative to the distance between the disk and the head.

An advantage of the present invention is that it obtains a magnetic recording medium with increased data storage capacity compared with conventional magnetic recording media.

An additional advantage of the present invention is that it provides a magnetic recording medium that has improved signal strength compared with that obtained from conventional recording media.

Another advantage of the present invention is that it provides a magnetic recording medium with improved signal-to-noise characteristics.

A further advantage of the present invention is that it obtains reduced spacing loss.

Another advantage of the present invention is that it improves the efficiency of the magnetic recording head during read and write operation.

An additional advantage of the present invention is that the magnetic recording medium exhibits significantly reduced phase interferences of the bit pattern.

A further advantage of the present invention is that the magnetic recording medium exhibits reduced losses in output signal due to finite pole and gap null effects.

Another advantage of the present invention is that the magnetic recording medium has improved bit shift characteristics.

An additional advantage of the present invention is that provision of additional, readily compatible layers in a multi-layer magnetic recording medium, including a thin layer of soft magnetic material, substantially enhances the magnetic recording properties of a magnetic recording medium.

A further advantage of the present invention is that interposition of a thin nonmagnetic layer between a soft magnetic material and a horizontal magnetic recording medium substantially enhances the magnetic recording properties of a magnetic recording medium.

Another advantage of the present invention is that the output signal is less sensitive to head flying height variations resulting from roughness of the medium surface.

The present invention may be practiced with a wide variety of horizontal or vertical recording materials, soft magnetic materials, nonmagnetic materials and substrates. In addition, conventional deposition methods may be employed to prepare the magnetic recording media of the present invention. Further, the above-described advantages may be achieved by the addition of a thin, low cost nonmagnetic layer using existing fabrication techniques and equipment.

<u>BRIEF DESCRIPTION OF THE DRAWINGS</u>

The invention will be better understood by reference to the figures in the drawings wherein like numbers denote like parts throughout and wherein:

Figure 1 is a cross-section of a magnetic recording medium in which a magnetic recording layer directly contacts a soft magnetic layer, as described in the prior art;

Figure 2 illustrates the reported frequency response for the magnetic recording medium prepared and tested according to the prior art;

Figure 3 illustrates the observed frequency response for the magnetic recording medium prepared as reported in the prior art;

Figure 4 is a cross-section of a magnetic recording medium according to the present invention;

Figures 5 and 6 illustrate comparisons of the frequency responses of a conventional magnetic recording medium and a magnetic recording medium according to the present invention;

Figure 7 illustrates the spacing loss relationships for a conventional medium and a magnetic recording medium according to the present invention;

Figure 8 illustrates the noise characteristics of a conventional magnetic recording medium;

Figure 9 illustrates the noise characteristics of a magnetic recording medium according to the present invention;

Figure 10 illustrates the bit shift characteristics of a conventional magnetic recording medium;

Figure 11 illustrates the bit shift characteristics of a magnetic recording medium according to the present invention;

Figure 12 is an isolated pulse plot of a conventional magnetic recording medium;

Figure 13 is an isolated pulse plot of a magnetic recording medium according to the present invention;

Figure 14 illustrates a schematic representation of a two-dimensional computer model used to study the

interaction of a conventional TF head with a conventional magnetic recording medium and a magnetic recording medium having a soft magnetic layer overlying the magnetic recording layer according to the present invention;

Figures 15A and 15B illustrate magnified views of the magnetic exchange coupling between the TF head and the conventional magnetic recording medium;

Figures 16A and 16B illustrate magnified views of the magnetic exchange coupling between the TF head and the magnetic recording medium with a soft magnetic layer overlying the recording layer according to the present invention;

Figure 17 illustrates a BH loop for a conventional magnetic recording medium;

Figure 18 is a BH loop for a magnetic recording medium according to the present invention;

Figure 19 is a cross-section of a magnetic recording medium according to the present invention in which the soft magnetic underlies the nonmagnetic layer and ~~the~~ magnetic recording layer;

Figure 20 illustrates a schematic representation of the two-dimensional computer model used to study the interaction of the TF head with a magnetic recording medium having a soft magnetic layer underlying the magnetic recording layer according to the present invention; and

Figures 21 and 21B illustrate magnified views of the magnetic exchange coupling between the TF head and a magnetic recording medium according to the present invention with soft magnetic layer underlying the magnetic recording layer.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Described herein is a magnetic recording medium having enhanced magnetic recording characteristics and

capable of producing improved signal quality, especially with respect to noise and strength. As a result, higher data densities may be achieved by maintaining a useful signal level. Need for expensive drive electronics to improve overall signal quality is reduced as well. Furthermore, the magnetic recording medium of the present invention can cooperate with advanced electronics to greatly extend data storage capacities. The '922 patent discloses a magnetic recording medium having a substrate 12 and a magnetic recording layer 16 in direct contact with a soft magnetic layer 18 as shown in Figure 1 and referred to here as the "direct contact" structure 10. The structure reportedly has improved signal strength at high frequencies and reduced spacing and reproduce gap losses, attributable to direct contact between the magnetic recording layer and the soft magnetic layer. Figure 2, taken from the related technical paper, shows the reported improvement in output signal at higher data densities in a magnetic recording medium where a saturating bias is applied to the "direct contact" structure. A gap null is apparent at about 70 kfci.

The improvement in magnetic recording properties based on this structure were not found to be reproducible. As illustrated in Figure 3, an attempt to verify these results shows instead that for the direct contact structure 10, signal amplitude is slightly improved at lower data densities but is degraded significantly at higher data densities as compared with the signal amplitude for a conventional magnetic recording medium. Nor did bias improve signal amplitude as was suggested in the '922 paper and the technical paper.

The present invention obtained reproducible enhanced magnetic recording performance over that described in the

'922 patent by interposition of a nonmagnetic "break" layer between the soft magnetic layer and the magnetic recording layer. This configuration, referred to as a "break layer" configuration 30, is illustrated in Figure 4. In particular, a magnetic recording layer 16 overlies the substrate 12 and an optional though preferred nucleating layer 14 and a nonmagnetic layer 22 lies between the magnetic recording layer 16 and a soft magnetic layer 18. A protective layer 20 of a material such as carbon overlies the soft magnetic layer.

Figure 5 compares the frequency responses for the break layer configuration 30 in the uppermost curve and a conventional magnetic recording disk in the lowermost curve. The uppermost curve shows a substantial gain in output signal compared to the lowermost curve across the full density range. Further, useful gain in signal is observed across a range of data densities from 1 kfci up to 70 kfci or more. Usable signal strength may be obtained even at higher data densities because of reduced spacing losses and gap length reduction, as described in detail below.

The curves in Figure 6 illustrate, at high resolution over shorter band width, the reduction in finite pole effects. The uppermost curve (for the break layer configuration 30) is smooth and lacks any significant head bumps in the frequency range studied. The lowermost curve (for the conventional magnetic recording medium) shows several head bumps, reducing the output signal at about 22 kfci, 35 kfci, 48 kfci and 60 kfci.

Figure 7 illustrates graphically the substantial reduction in overall spacing loss, i.e., read and write spacing losses combined, achieved over a wide range of head flying heights, d, by a magnetic recording medium incorporating break layer configuration 30 as compared with a conventional magnetic recording medium. The

signals were recorded with a wavelength (λ) of 28.5 microinches.

The classical Wallace spacing losses for the conventional medium were measured to be 133 d/λ, while those for the break layer configuration 30 was 71 d/λ. A comparison of the slopes for these equations (133 versus 71) indicates that signal sensitivity to flying height variation is reduced by nearly a factor of two. This reduction in sensitivity means that even with variations in surface roughness across a magnetic recording disk and attendant variations in flying height, at least adequate magnetic recording performance is observed. Further, across a wide range of flying heights, significant gain is observed in the signals for the break layer configuration as compared with those for the conventional recording medium.

Figures 8 and 9 compare qualitatively the signal-to-noise ratio (SNR) obtained from the break layer configuration 30 with that from the conventional magnetic recording disk, respectively. A close examination of the curves reveals that from a magnetic recording medium incorporating the break layer configuration 30, little, if any, noise over and above the "floor" of the output signal is detected, the "floor" being defined by the amount of noise in the signal introduced by the measuring equipment used. In addition, the amplitude is increased significantly by about 10 dB. As a result, the proportion of usable signal, SNR, from each bit is increased..

Improved bit shift is an indication of the improved interaction between the head and magnetic recording medium. Figures 10 and 11 illustrate the improved bit shift data obtained for the magnetic recording media of the present invention as compared with that from the conventional magnetic recording medium, respectively.

Specifically, a comparison of the curves shows that with a magnetic recording medium incorporating the break layer configuration 30, a soft error rate of 1 bit in 10^8 bits at which a bit shift of 10 nanoseconds (nsec) can be maintained even at data densities of 50 kfci. In a conventional magnetic recording medium at such a data density, the bit shift increases to a significantly higher 13.3 nsec.

Figures 12 and 13 illustrate the pulse width at 50% of maximum height, PW50, of isolated signal pulses read from the conventional magnetic recording medium and the break layer configuration 30, respectively. In Figure 12, the PW50 is about 72 nsec. Some asymmetries, head bumps and other noises such as "wiggle" appear in the "shoulders" of the signal. In contrast, for the break layer configuration 30, a significantly narrower and cleaner signal is observed. PW50 is reduced to about 55 nsec and the signal shows neither head bumps nor asymmetries, and virtually no noise in the wings.

From these cumulative results, it unexpectedly appears that with the break layer configuration 30, data densities could be increased by about a factor of 2.

It is believed that the observed improvements in magnetic recording properties are due to the interruption of effects of magnetic exchange coupling that results from the interposition of the break layer between the magnetic recording layer and the soft magnetic layer. Specifically, it is submitted that the break layer interrupts the magnetic exchange coupling between the soft magnetic layer and the magnetic recording layer, allowing the latter two layers to react separately to the flux induced by the bias current in the head.

Figure 14 illustrates schematically a two-dimensional computer model used to study the reduction in spacing losses resulting upon application of a bias

current to a medium having a soft magnetic layer M and break layer overlying the magnetic recording layer and being scanned by a conventional TF head 40 with the intent to read bit 49. Spacing losses are qualitatively indicated by the changes in the coupling of magnetic flux from the given bit through an equivalent magnetic reluctance representing the presence and operation of the schematically shown head core 45 upon application of a small (about 1 milliamp) DC bias current, I_B. The resultant signals would be detected as voltages, V_S. Additional parameters of the model were as follows: poles 42A, 42B of head 40 separated by a 0.44 micron gap with a head flying height d of 5 microinches.

Figures 15A and 15B illustrate on magnified scales the interaction of a TF head 40 with a conventional magnetic recording medium, during the playback or read operation. Flux lines 44, 46, 48 from surrounding bits 50, 52 couple with the head poles 42A and 42B, with flux from these bits coupling through the equivalent magnetic reluctance of the head core 45 interconnecting the poles. Other flux lines 54, 56 emerge from adjacent bits 50, 52, also coupling through the equivalent magnetic reluctance. As a result, the output signal detected by the head is a product of the flux from more than one bit.

Figures 16A and 16B illustrate on magnified scales the interaction of the head 40 with a magnetic recording medium incorporating the break layer configuration 30. The magnetic recording medium consisted of a substrate, a 775Å magnetic recording layer, a 100Å carbon break layer, a 700Å keeper layer and a 250Å carbon protective layer. Upon application of a saturating bias flux from the head 40, flux lines 56, 58, otherwise retained by the keeper layer above the bit 49, 'leak' along the keeper layer toward the head. Flux from all other bits 50, 52 remains keepered, as indicated by flux lines 57, 59.

Even at large distances along the keeper layer relative to the distance between the head 40 and the medium, essentially all of the leaking flux couples magnetically with the head through the equivalent magnetic reluctance connecting the poles. Because the only flux sensed by the head is that from the particular bit to be read and this flux is more efficiently coupled, head efficiency is improved. This improved efficiency is manifested in the improved magnetic recording properties observed.

The magnetic exchange coupling theory is supported by a qualitative comparison of the magnetic characterizations of these magnetic recording media. Figures 17 and 18 are the BH loops of a conventional horizontal magnetic recording medium and of the break layer configuration 30, respectively. Figure 17 depicts a loop of typical configuration, indicating that the medium switches smoothly throughout the cycle of polarity changes in the applied magnetic field. The shape of the BH loop in Figure 18 contrasts sharply. The height of the BH loops differs, with the total height of the BH loop (i.e., dimension along the B axis) dependent on the sum of the moments of the soft magnetic and magnetic recording layers. The observed discontinuities or "bumps" in the BH loop suggest that magnetization of the NiFe layer 18 and the magnetic layer 16 switch independently. It is submitted that the discontinuities manifest a break of the magnetic exchange coupling between the soft magnetic layer and the magnetic recording layer. The location of the bumps indicates the relative proportions of the soft magnetic material and magnetic recording material in a magnetic recording medium incorporating the break layer configuration.

Conventional materials may be used in preparation of the magnetic recording medium of the present invention incorporating break layer configuration 30. Typically,

substrate 12 is a nickel-phosphorus-plated aluminum disk used in Winchester-type hard disk drive technology. Nonmetallic substrates such as glass, carbon and ceramic materials also may be suitable. The disk surface may require cleaning or other treatments to enhance adhesion of the subsequently deposited layer. In addition, surface treatments such as texturizing or polishing are known to promote a desired crystalline morphology in the subsequently deposited magnetic recording layer. Alternatively, substrate 12 may be a tape suitable for conventional magnetic tape recording, e.g., polyvinylidene chloride, or a sheet of thermoplastic material, such as polyethyleneterephthalate, suitable for use in conventional floppy disks. Other surface treatments may be employed to prepare the latter substrates for subsequent deposition.

The magnetic recording layer 16 may be formed from any of a variety of magnetic compositions useful as horizontal and vertical recording materials, as is well known in the art. For a magnetic recording disk according to the present invention, the thickness of the magnetic recording layer 16 can range from 200Å to 1000Å, with 300Å to 700Å being most preferred.

Polycrystalline magnetic recording materials may require deposition of a nucleating layer 14 beneath the magnetic recording layer 16 to help promote the desired morphology and crystalline growth and therefore magnetic properties in the magnetic recording layer 16. For example, for polycrystalline magnetic recording materials based on cobalt alloys such as cobalt-chromium (CoCr) or cobalt-nickel (CoNi), a layer of chromium (Cr) 14 applied between the substrate 12 and magnetic layer 16 may be necessary to help establish the desired hexagonal close packed (hcp) growth necessary in the CoCr or CoNi magnetic recording layer 16. For a magnetic recording

disk according to the present invention, the nucleating layer thickness is preferably between about 100Å and about 2000Å, with the most preferred thickness between about 200Å and about 1000Å.

The nonmagnetic layer 22 may be formed from a wide variety of nonmagnetic materials that are immiscible with the magnetic recording and soft magnetic layers and do not upset crystal structure of the adjacent magnetic layers. Examples of such materials include metals such as chromium, molybdenum and tungsten, metalloids such as carbon, silicon and germanium, titanium and alloys of these elements, glasses, alumina and other refractory materials, elastomeric materials such as those sold under the trade name PARALENE™ and even lacquer-like materials. Preferred nonmagnetic break layer materials are chromium, carbon and silicon, with the latter being most preferred. The crystalline morphology of the nonmagnetic break layer material may be an important consideration in its selection, since its morphology may influence epitaxy and therefore, magnetic properties of subsequently deposited layers. As a consequence, introduction of additional nonmagnetic layers between the magnetic recording layer and the soft magnetic layer to effect a particular crystalline morphology in either the soft magnetic layer or the magnetic recording layer is considered to be within the scope of the present invention.

The thickness of the nonmagnetic break layer should be sufficient to interrupt magnetic exchange coupling between the magnetic recording layer and the soft magnetic layer. However, it is desirable that the thickness of the nonmagnetic layer be sufficiently thin so as to avoid interference with the flux-induced signal, e.g., by contributing to additional spacing losses during the write process. Therefore, generally, only a thin layer is necessary to achieve this effect, with a

thickness of between about 15Å to about 300Å being adequate. Thicknesses between about 25Å and about 150Å are preferred. However, in some instances, a thin layer, approximating the thickness of a monolayer, sufficient to fully interrupt the magnetic exchange coupling between the magnetic recording layer and the soft magnetic layer, may be used.

The soft magnetic layer 18 may be formed from a wide variety of soft magnetic materials well known in the art of drive head manufacture, including pure Ni, Fe, or Co, or their alloys including NiFe (sold under the trade name PERMALLOY™), or aluminum-iron-silicon (AlFeSi, sold under the trade name SENDUST™), cobalt-zirconium-niobium (CoZrNb), and other alloys. Ideally, the soft magnetic material is corrosion-resistant. Other materials which may be suitable for use as the soft magnetic layer are amorphous alloys or polycrystalline materials having near zero magnetostriction.

In general, the thickness of the soft magnetic layer should be sufficient to retain or keeper all of the flux from the data recorded in the magnetic recording layer. This effect may be achieved by a layer of a single soft magnetic material or a lamination of several layers of one or more soft magnetic materials separated by thin nonmagnetic break layers. The actual thickness necessary is a function of the moment of the material used as the soft magnetic layer. For example, for a magnetic recording disk according to the present invention, a soft magnetic layer 18 composed of NiFe may be between about 700Å and about 1200Å. Most preferred is a thickness about 750Å. For a soft magnetic layer 18 composed of CoZrNb, a thickness of about 350Å is adequate, as predicted based upon the moment for CoZrNb being about twice that of NiFe.

Although the break layer configuration 30 is illustrated with the soft magnetic layer 18 overlying the magnetic recording layer 16, the opposite configuration is contemplated as within the scope of the present invention. That is, a break layer configuration 60, as shown in Figure 19, may be prepared with the soft magnetic layer 18 being deposited directly on the substrate 12 and nucleating layer 14, followed by the nonmagnetic layer 22 and then the magnetic recording layer 16.

Figure 20 illustrates schematically the two-dimensional computer model for a magnetic recording medium incorporating break layer configuration 60. Note that the soft magnetic layer M lies underneath the magnetic recording layer where bits 49, 50 and 52 are located. The nonmagnetic break layer 22 separates the soft magnetic layer from the magnetic recording layer. Otherwise, the model parameters are identical to those described in connection with Figure 14.

The model predicts that such a medium can achieve improvements in magnetic flux coupling and head efficiency of at least comparable magnitudes to those observed for the medium incorporating break layer configuration 30 in which the soft magnetic layer overlies the magnetic recording layer.

Figures 21A and 21B illustrate on magnified scales the interaction of the TF head 40 with the medium during the read operation. Once again, upon application of the bias current, flux lines 56 and 58, otherwise retained by the keeper layer underlying bit 49, 'leak' along the keeper layer toward the head. Flux from all other bits 50, 52 remains keepered, as indicated by flux lines 57, 59. As before, head efficiency is improved by increased coupling of the flux from the single transition or bit 49 with the head poles.

The final layer 20 protects the magnetic recording medium according to the present invention from wear and the corrosive effects of any vapors present within the magnetic signal processing device. As known to the art, the protective outer layer 20 may be composed of metals including rhodium, or nonmetallic materials such as carbon and inorganic non-metallic carbides, nitrides and oxides, e.g., silica or alumina. For a magnetic recording disk, the thickness may be between about 200Å and about 350Å; a carbon thickness between about 225Å and about 350Å is most preferred.

A magnetic recording medium having the break layer configuration 30 is prepared by the sequential deposition of the layers onto the substrate 12. A preferred configuration employs a 400Å Cr underlayer 14, a 500Å cobalt-chromium-tantalum (CoCrTa) layer 16, a 25Å carbon break layer 22, a 700Å NiFe layer 18 and a 300Å protective carbon layer 20. An alternate preferred configuration employs a 400Å Cr underlayer 14, a 500Å CoCrTa layer 16, a 25Å silicon break layer, a 400Å CoZrNb layer 18 and a 300Å protective carbon layer 20.

Deposition of the various layers may be achieved according to means well-known in the art, for example, by sputtering, plating, evaporation or other thin film deposition methods, alone or in combination. Other means more exotic relative to conventional magnetic recording disk manufacturing processes, such as chemical oxidation, coating, spinning, baking or polymerization, may also be used to deposit the desired thin films, particularly those methods that are adaptable to nonmetallic materials.

In recognition of the importance of the observed discontinuity in magnetic switching of the soft magnetic layer and the magnetic recording layer, a key factor in achieving the structure described in the present

invention is maintenance of the integrity of the magnetic recording layer 16 until the subsequent deposition of the nonmagnetic layer 18. In a sputtering apparatus, film integrity is quite easily maintained by virtue of an evacuated environment within the apparatus that minimizes oxidation and contamination of each layer until a subsequent layer is deposited. The multilayer configuration of the media of the present invention was produced in an in-line DC magnetron sputtering process and apparatus, such as those described in co-pending Application Serial No. 07/681,866, incorporated herein by reference, where interlayer integrity may be easily maintained in the highly evacuated multiple chamber sputtering apparatus. Other deposition parameters may be selected to optimize film properties such as thickness and morphology to tailor the magnetic properties of the magnetic recording medium prepared. For example, in such a sputtering process, relatively low sputtering pressure (about 2 microns argon) may favor morphological structures that enhance magnetic properties of the sputtered films.

As discussed earlier, application of only a small bias current is necessary to saturate the soft magnetic layer in the region of the bit to be read. The actual current applied may vary with the TF head used, its efficiency, and the thickness of the soft magnetic layer in the magnetic recording medium. However, the bias current need be only of a magnitude that is sufficient to achieve saturation and typically ranges between about 0.5 milliamps (mA) to about 1.5 mA. Such a current may be either AC or DC, though preferably is DC.

In summary, the magnetic recording media of the present invention improves magnetic recording properties by provision of a relatively thinner nonmagnetic layer interposed between a soft magnetic layer and a thin

magnetic recording layer. Overall signal strength and quality are increased even at substantially higher data densities than are achievable with conventional magnetic recording media. A wide variety of conventional materials and fabrication techniques may be used to prepare the novel magnetic recording media of the present invention.

CLAIMS

What is claimed is:

1. A magnetic recording medium, comprising:

a) a substrate;

b) a thin magnetic recording layer;

c) a soft magnetic layer; and

d) a relatively thinner nonmagnetic layer interposed between the magnetic recording layer and the soft magnetic layer.

2. A magnetic recording medium, according to Claim 1, wherein the medium further comprises a nucleating layer directly underlying the magnetic recording layer.

3. A magnetic recording medium, comprising:

a) a disk substrate;

b) a thin magnetic recording layer deposited on the substrate;

c) a relatively thinner nonmagnetic layer deposited on the magnetic recording layer; and

d) a soft magnetic layer deposited directly on the nonmagnetic layer such that the nonmagnetic layer physically contacts the magnetic recording layer and the soft magnetic layer.

4. A magnetic recording medium, comprising:

a) a nickel-phosphorus plated aluminum disk having a circumferentially textured surface;

b) a nucleating layer deposited directly on the surface, the nucleating layer consisting of chromium;

c) a thin magnetic recording layer deposited directly on the nucleating layer, the magnetic recording layer consisting of cobalt alloys selected from the group

consisting of CoNiCr, CoCrTa, CoCrPt, CoNiPt and CoNiCrPt;

d) a relatively thinner nonmagnetic layer deposited directly on the magnetic recording layer, the nonmagnetic layer consisting of a material selected from the group consisting of silicon, carbon and chromium;

e) a soft magnetic layer deposited directly on the nonmagnetic layer, the soft magnetic layer consisting of a material selected from the group consisting of CoZrNb, AlFeSi, and NiFe; and

f) a protective layer deposited directly on the soft magnetic layer, the protective layer consisting of carbon.

5. A magnetic recording medium according to Claim 4, wherein the nucleating layer is between about 100Å and about 2000Å.

6. A magnetic recording medium according to Claim 5, wherein the nucleating layer is between about 200Å and about 1000Å.

7. A magnetic recording medium according to Claim 4, wherein the magnetic recording layer is between about 200Å and about 1000Å.

8. A magnetic recording medium according to Claim 7, wherein the magnetic recording medium is between about 300Å and about 700Å.

9. A magnetic recording medium according to Claim 4, wherein nonmagnetic layer is between about 15Å and about 300Å.

10. A magnetic recording medium according to Claim 9, wherein the nonmagnetic layer is between about 25Å and about 100Å.

11. A magnetic recording medium according to Claim 4, wherein the thickness of the soft magnetic layer is sufficient to act as a keeper layer.

12. A magnetic recording medium according to Claim 11, wherein the soft magnetic layer is NiFe with a thickness between about 700Å and about 1200Å.

13. A magnetic recording medium according to Claim 12, wherein the soft magnetic layer is NiFe with a thickness about 750Å.

14. A magnetic recording medium according to Claim 4, wherein the soft magnetic layer is CoZrNb with a thickness between about 250Å and about 600Å.

15. A magnetic recording medium according to Claim 14, wherein the soft magnetic material is CoZrNb with a thickness about 350Å.

16. A magnetic recording medium according to Claim 4, wherein the protective layer is between about 200Å and about 350Å.

17. A magnetic recording medium according to Claim 4, wherein the protective layer is between about 225Å and about 350Å.

18. A method for preparing a magnetic recording medium, comprising the steps of:

a) providing a substrate;

b) depositing a thin magnetic recording layer on the substrate;

c) maintaining the integrity of the magnetic recording layer;

d) depositing a relatively thinner nonmagnetic layer directly on the magnetic recording layer; and

e) depositing a soft magnetic layer directly on the nonmagnetic layer such that the nonmagnetic layer physically contacts the magnetic recording layer and the soft magnetic layer.

19. A method for preparing a magnetic recording medium, comprising the steps of:

a) providing disk substrate;

b) sputtering a thin magnetic recording layer on the disk substrate;

c) sputtering a relatively thinner nonmagnetic layer directly on the magnetic recording layer; and

d) sputtering a soft magnetic layer directly on the nonmagnetic layer such that the nonmagnetic layer physically contacts the magnetic recording layer and the soft magnetic layer.

20. A method of preparing a magnetic recording medium, comprising the steps of:

a) providing a nickel-phosphorus plated aluminum disk substrate, the substrate having a circumferentially textured surface;

b) sputtering a nucleating layer directly on the textured surface;

c) sputtering a thin magnetic recording layer directly on the nucleating layer;

d) maintaining the integrity of the magnetic recording layer;

e) sputtering a relatively thinner nonmagnetic layer on the magnetic recording layer;

f) sputtering a soft magnetic layer on the nonmagnetic layer such that the nonmagnetic layer is positioned between and physically contacts the magnetic recording layer and the soft magnetic layer; and

g) sputtering a protective layer on the soft magnetic layer.

21. A magnetic recording medium for use in a magnetic recording system in which a bias flux applied to the medium defines a region for signal transfer, comprising:

a) a substrate;

b) a thin magnetic recording layer;

c) a relatively thinner nonmagnetic layer disposed directly on the magnetic recording layer; and

d) a soft magnetic layer disposed directly on the nonmagnetic layer, the soft magnetic layer having a thickness sufficient to keeper the signal.

22. A magnetic recording medium for use in a magnetic recording system in which a bias flux applied to the medium defines a region for signal transfer, comprising:

a) a disk substrate;

b) a nucleating layer disposed directly on the substrate;

c) a thin magnetic recording layer disposed directly on the nucleating layer;

d) a relatively thinner nonmagnetic layer disposed directly on the magnetic recording layer;

e) a soft magnetic layer disposed directly on the nonmagnetic layer, the soft magnetic layer having a thickness sufficient to keeper the signal; and

d) a protective layer disposed directly on the soft magnetic layer.

23. A magnetic recording medium according to Claim 21, wherein the nonmagnetic break layer has a thickness between about 25Å and about 300Å.

24. A magnetic recording medium according to Claim 21, wherein the nonmagnetic break layer has a thickness between about 25Å and about 150Å.

25. A magnetic recording medium according to Claim 21, wherein the nonmagnetic break layer comprises a material selected from the group comprising silicon, carbon, chromium, silicon dioxide and alumina.

26. A magnetic signal processing device, comprising:

a) a magnetic recording medium having a thin layer of highly magnetically coercive material for storing and receiving magnetic signals, a layer of soft magnetic material and a relatively thinner nonmagnetic layer therebetween;

b) a magnetic transducer positioned relative to the magnetic medium such that the transducer stores magnetic signals in and receives magnetic signals from the magnetic recording medium;

c) means for moving the medium and head relative to each other; and

d) means for generating a bias flux in the transducer which saturates a region of the layer of soft magnetic material to direct signal transfers between the transducer and the magnetic medium.

27. A method of processing magnetic signals using a magnetic transducer to store and receive magnetic signals and an adjacent magnetic recording medium with respect to

which the magnetic signals are transferred, comprising the steps of:

a) providing a magnetic recording medium having a thin, highly magnetically coercive magnetic recording layer, a soft magnetic layer and a relatively thinner nonmagnetic layer therebetween;

b) generating a magnetic bias flux in the transducer that saturates a region of the soft magnetic layer such that a magnetic flux from data stored in the adjacent region of the magnetic recording layer magnetically couples with the magnetic transducer.

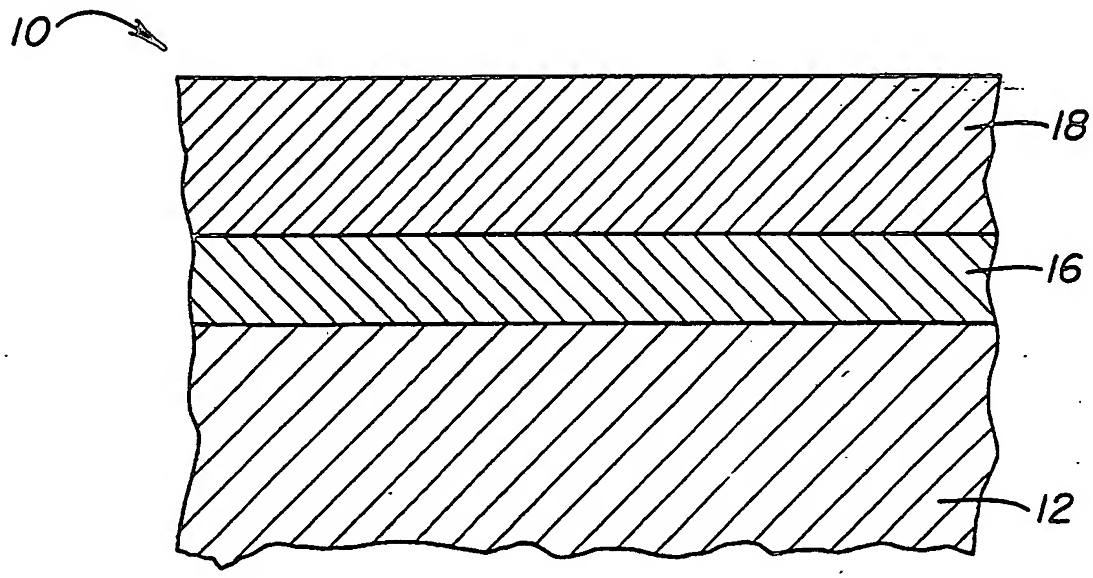


FIGURE 1 (PRIOR ART)

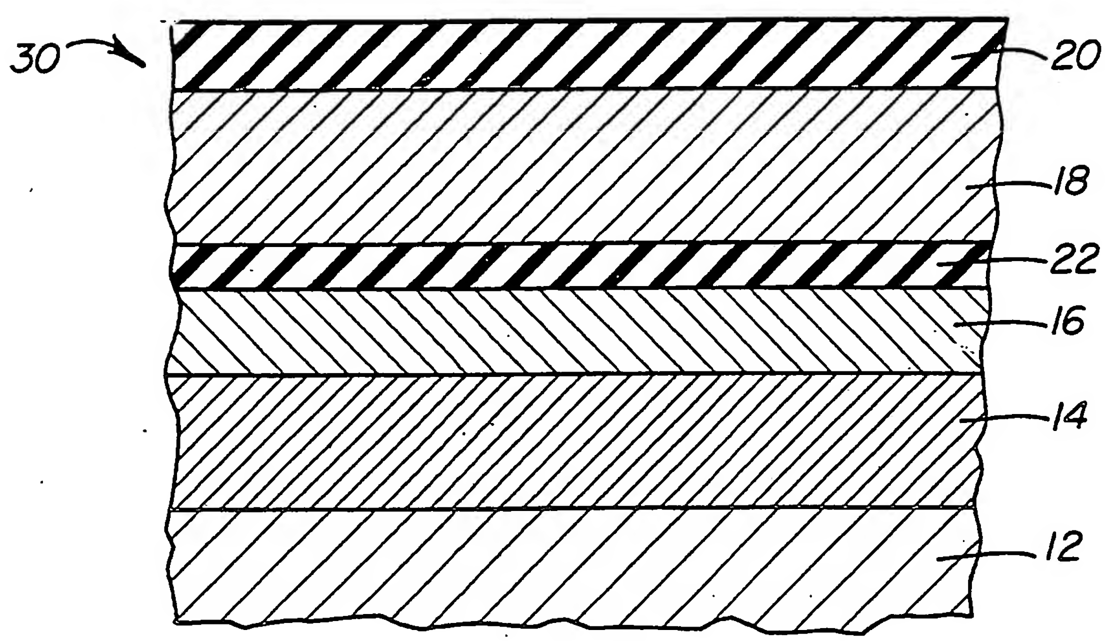
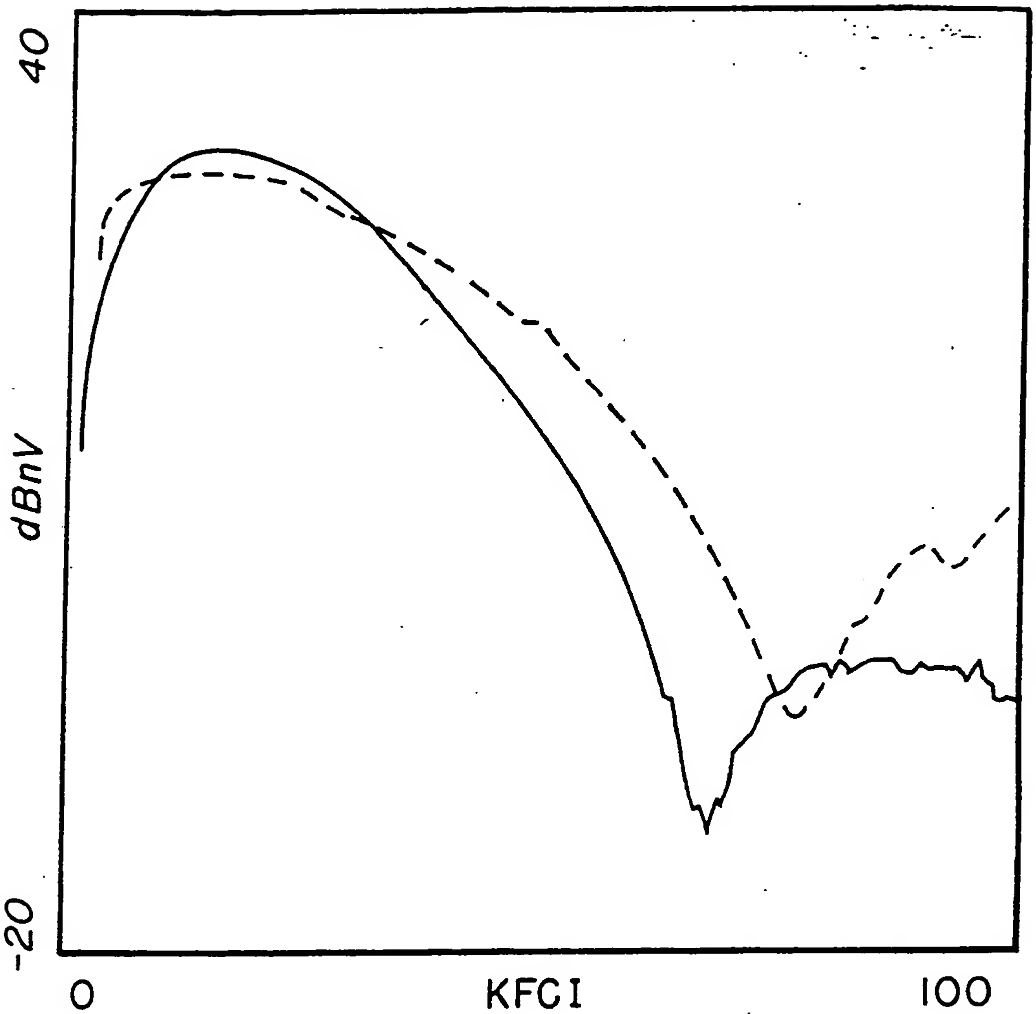


FIGURE 4



—— UNKEEPERED
HEAD CURRENT = 11 mA

--- KEEPERED
HEAD CURRENT = 12 mA
HEAD BIAS = 2.5 mA

FIGURE 2 (PRIOR ART)

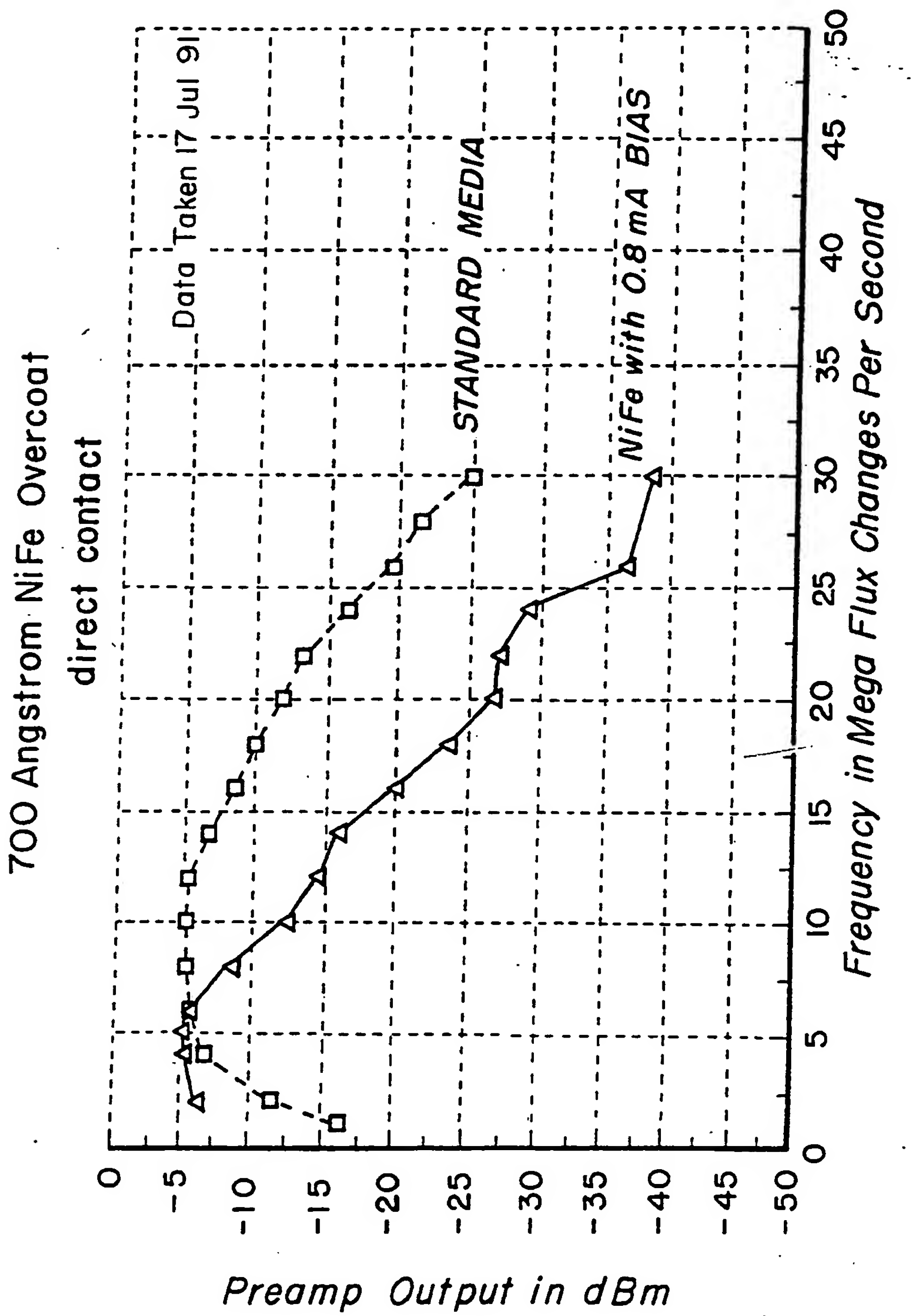

700 Angstrom NiFe Overcoat
direct contact
Data Taken 17 Jul 91
STANDARD MEDIA
NiFe with 0.8 mA BIAS
0
5
10
15
20
25
30
35
40
45
50
Frequency in Mega Flux Changes Per Second
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
Preamp Output in dBm

FIGURE 3

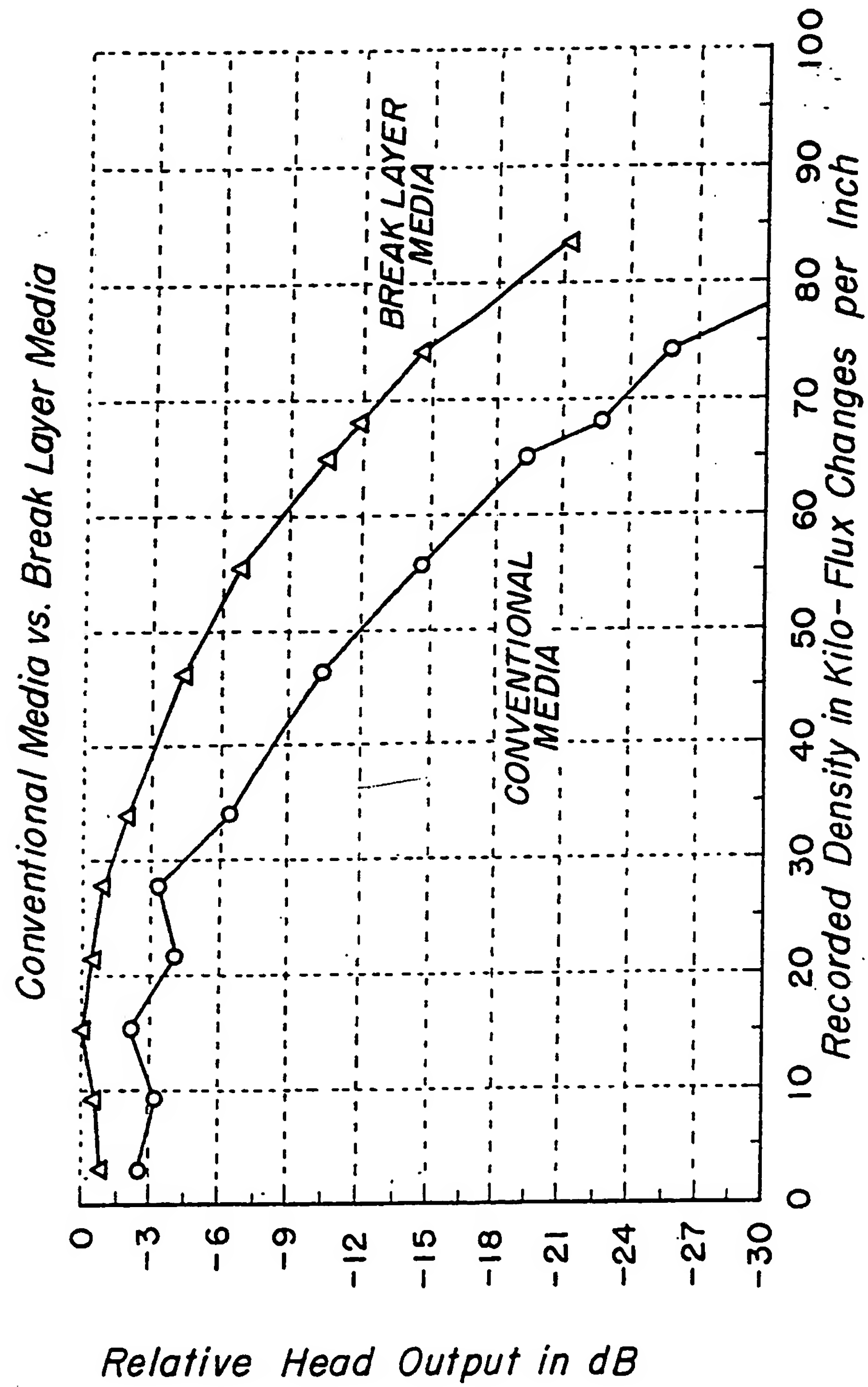

Conventional Media vs. Break Layer Media
BREAK LAYER MEDIA
CONVENTIONAL MEDIA
Recorded Density in Kilo-Flux Changes per Inch
0
10
20
30
40
50
60
70
80
90
100
Relative Head Output in dB
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30

FIGURE 5

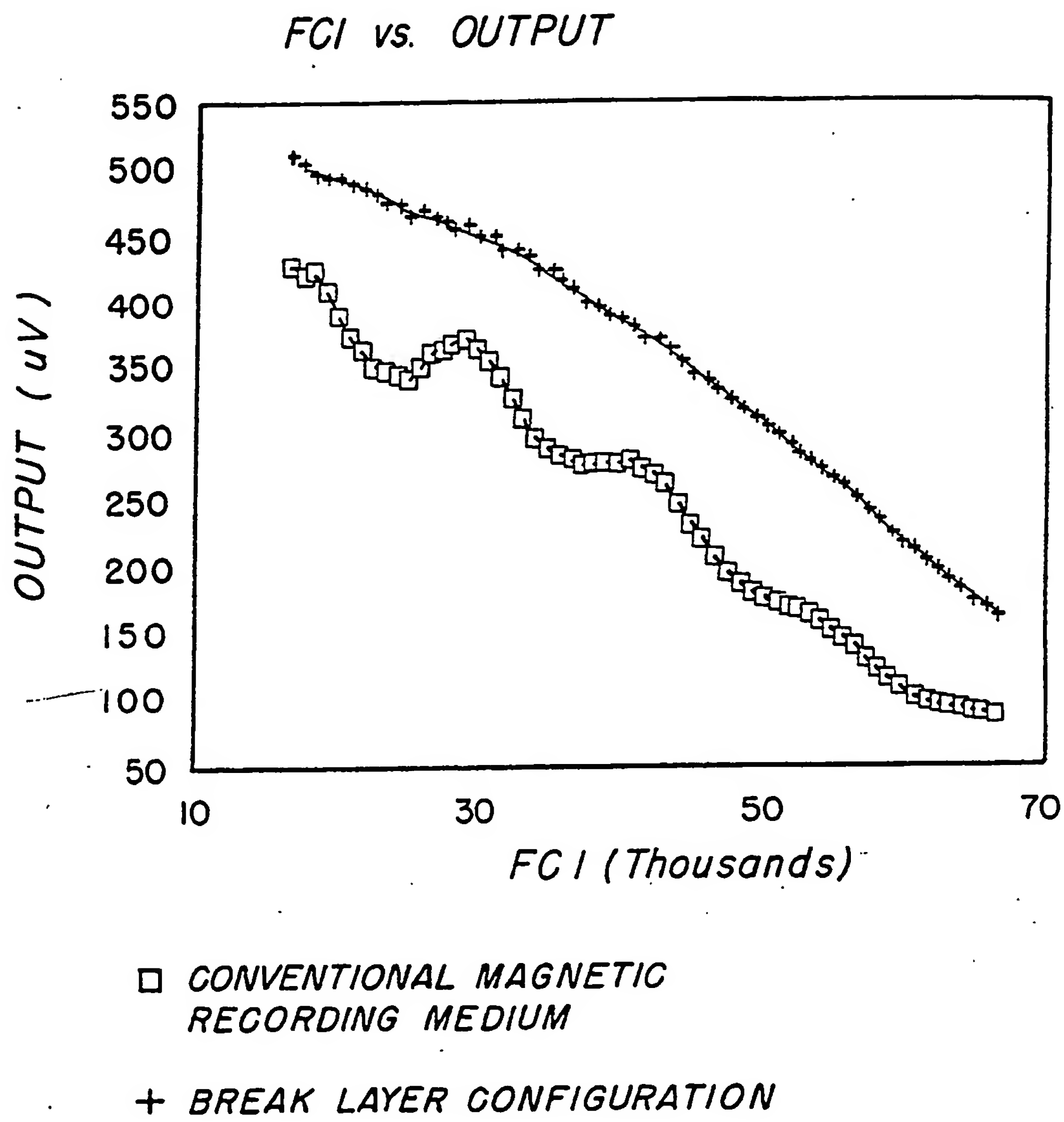

FCI vs. OUTPUT
OUTPUT (uV)
550
500
450
400
350
300
250
200
150
100
50
10
30
50
70
FC I (Thousands)
CONVENTIONAL MAGNETIC RECORDING MEDIUM
BREAK LAYER CONFIGURATION

FIGURE 6

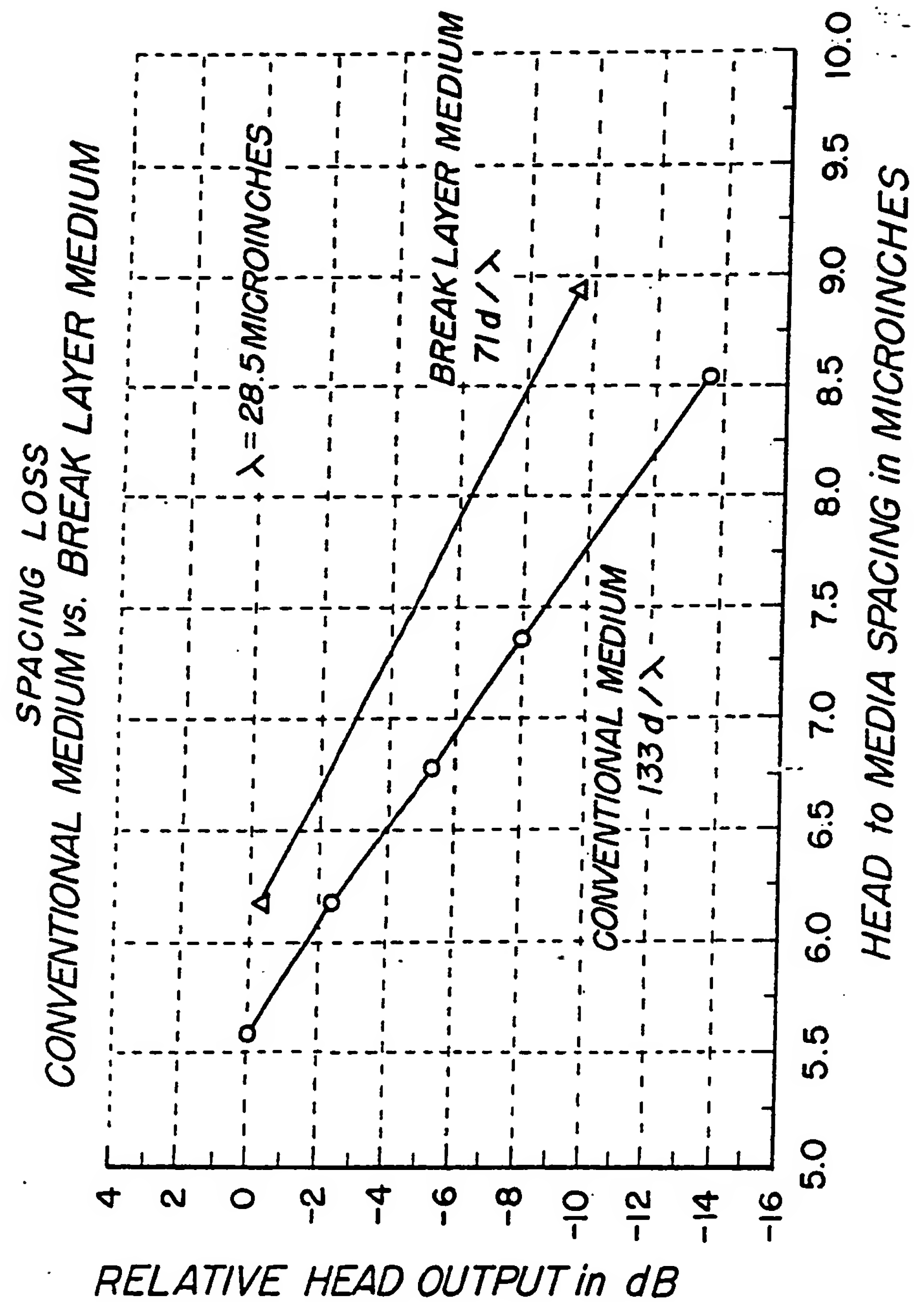

SPACING LOSS
CONVENTIONAL MEDIUM vs. BREAK LAYER MEDIUM
λ = 28.5 MICROINCHES
BREAK LAYER MEDIUM
71 d / λ
CONVENTIONAL MEDIUM
133 d / λ
RELATIVE HEAD OUTPUT in dB
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
HEAD to MEDIA SPACING in MICROINCHES
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0

FIGURE 7

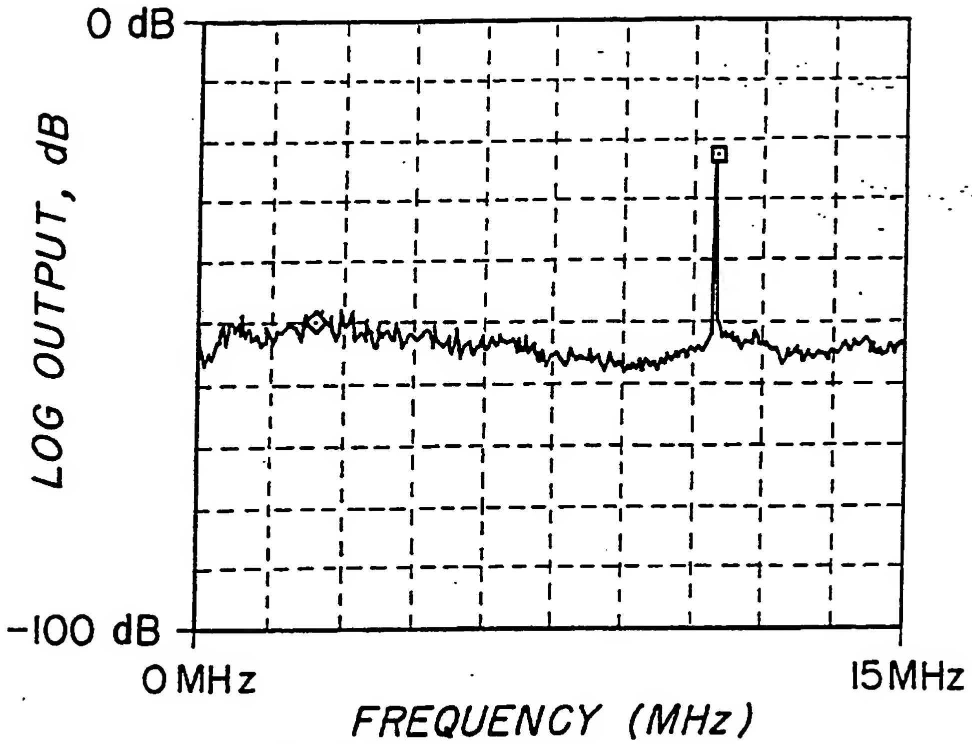


FIGURE 8 (PRIOR ART)

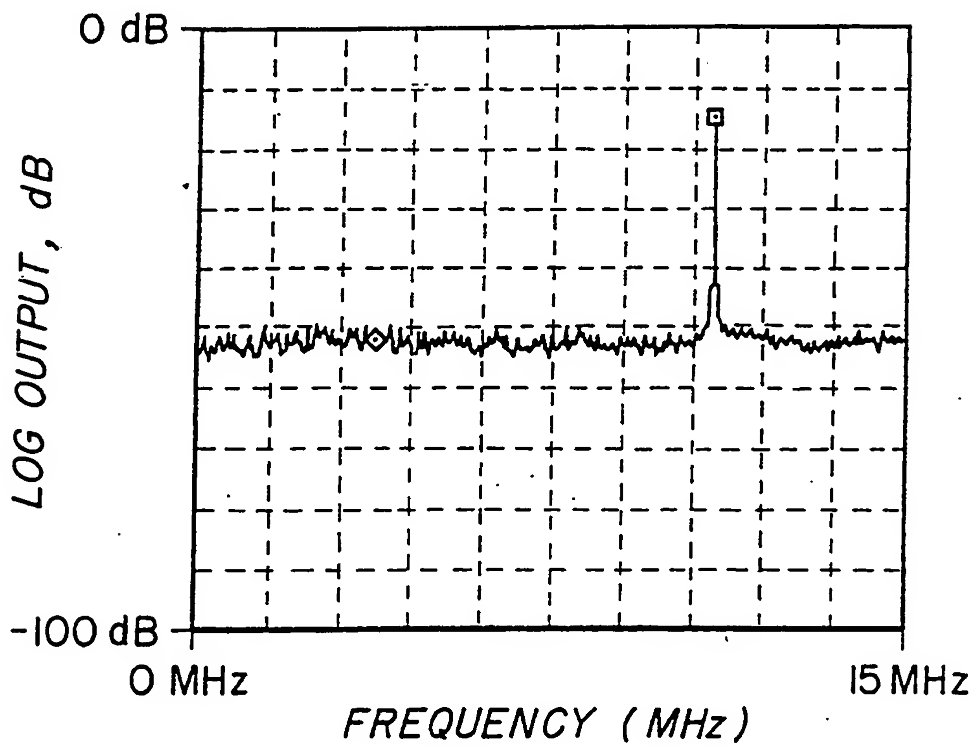


FIGURE 9

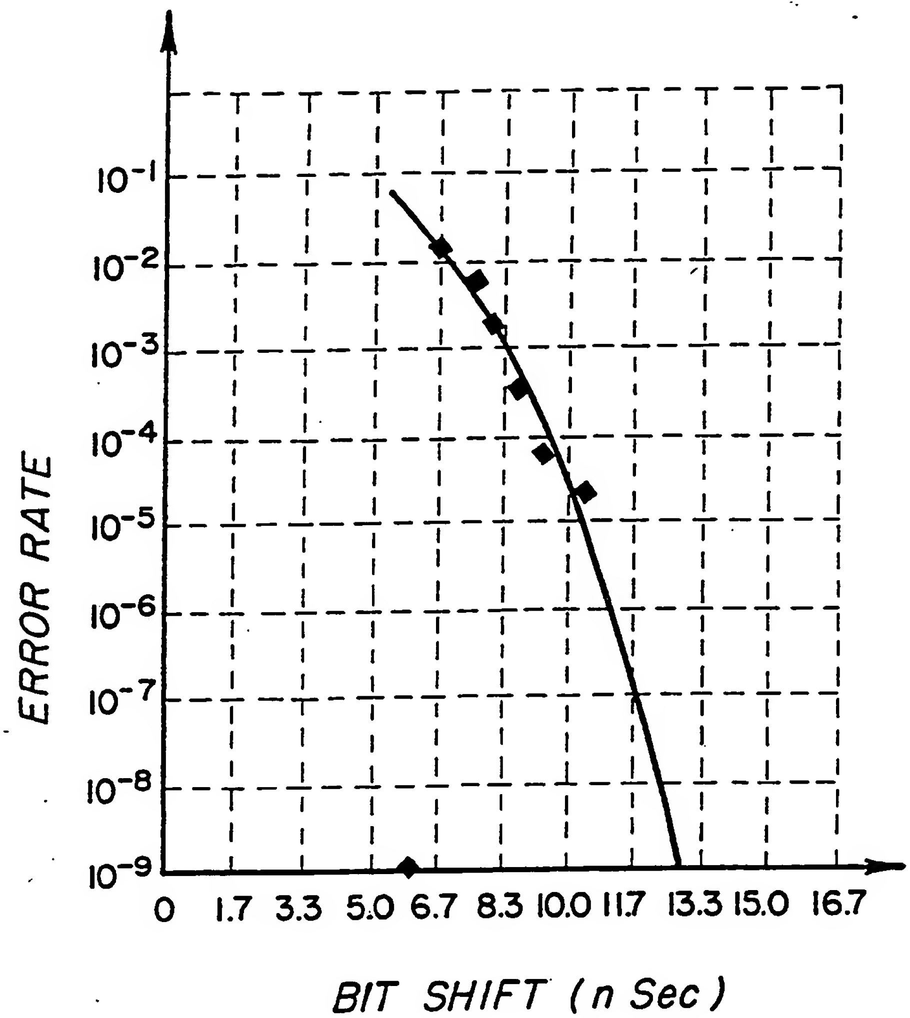


FIGURE 10 (PRIOR ART)

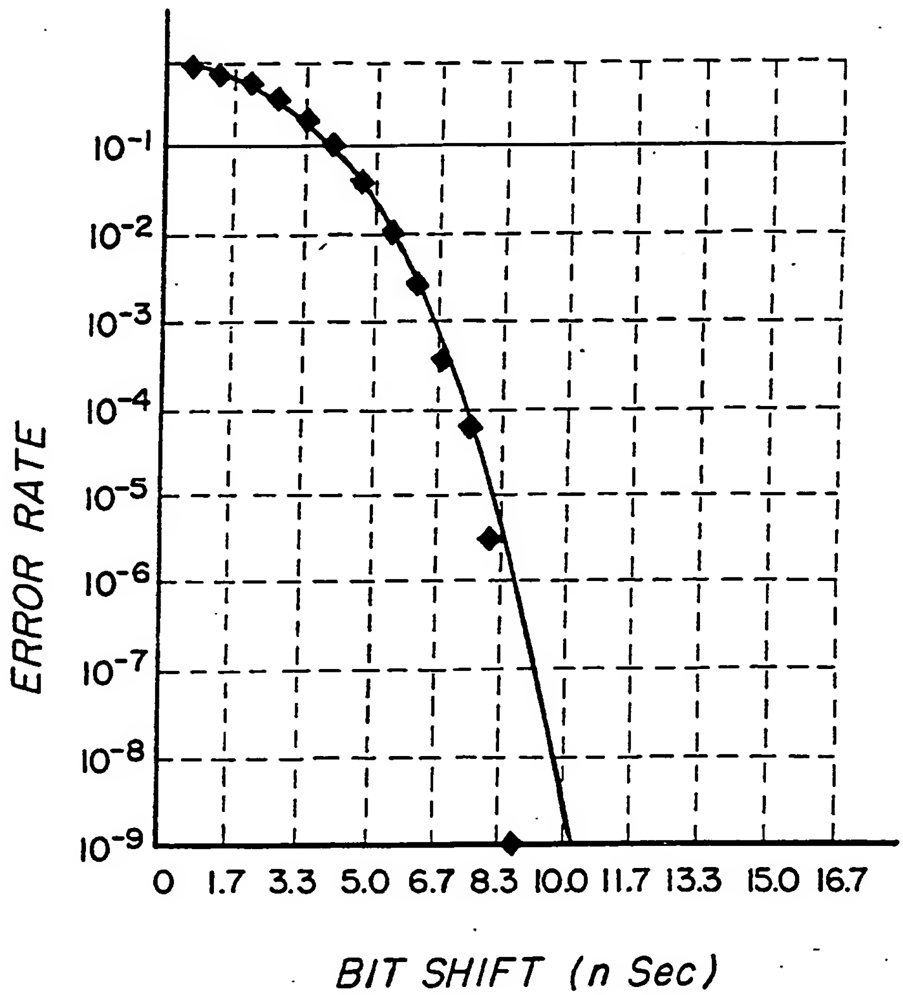

ERROR RATE
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
0 1.7 3.3 5.0 6.7 8.3 10.0 11.7 13.3 15.0 16.7
BIT SHIFT (n Sec)

FIGURE 11

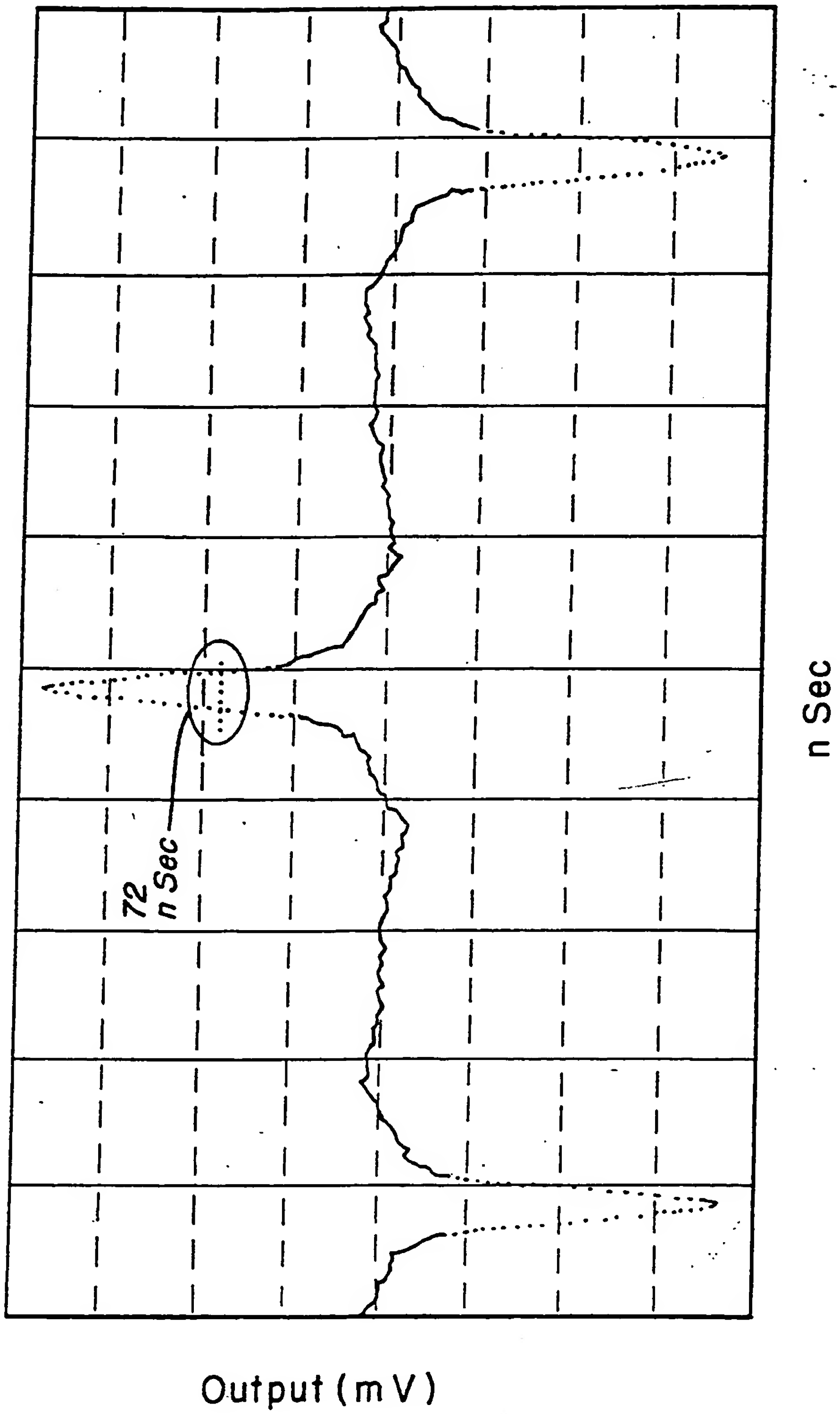


FIGURE 12 (PRIOR ART)

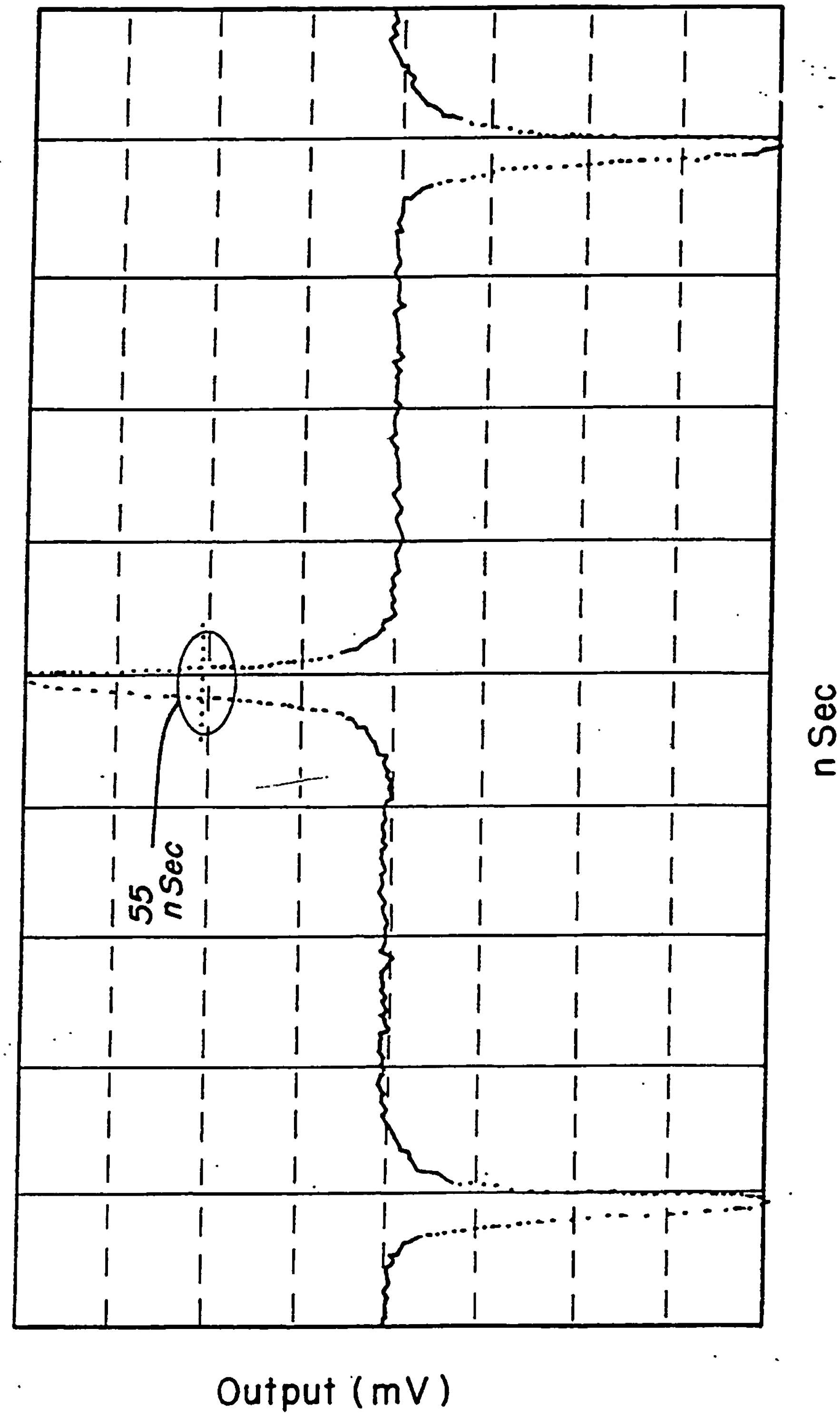


FIGURE 13

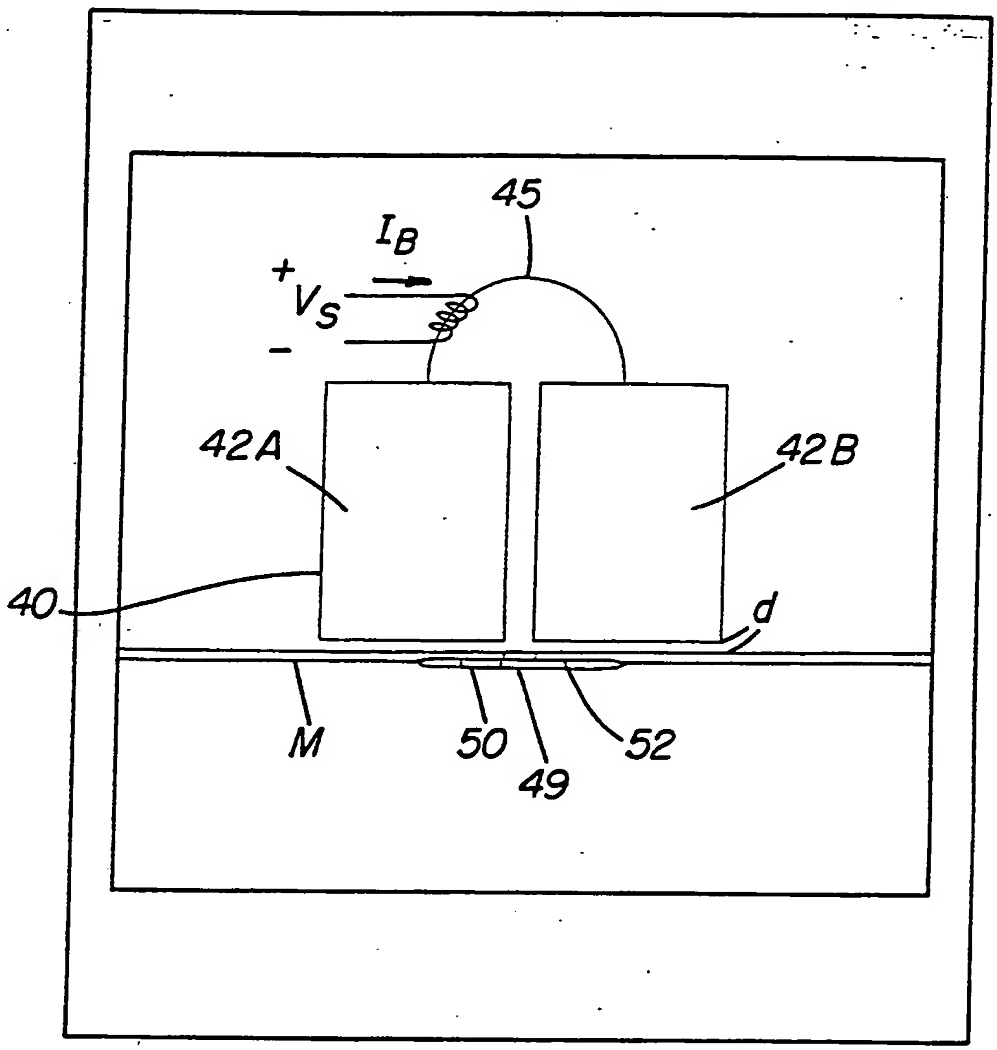


FIGURE 14

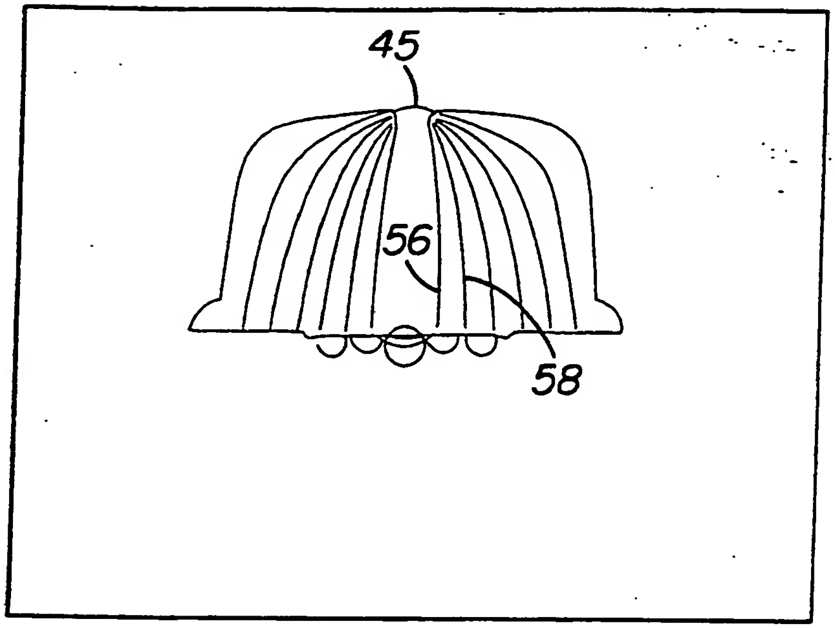


FIGURE 16A

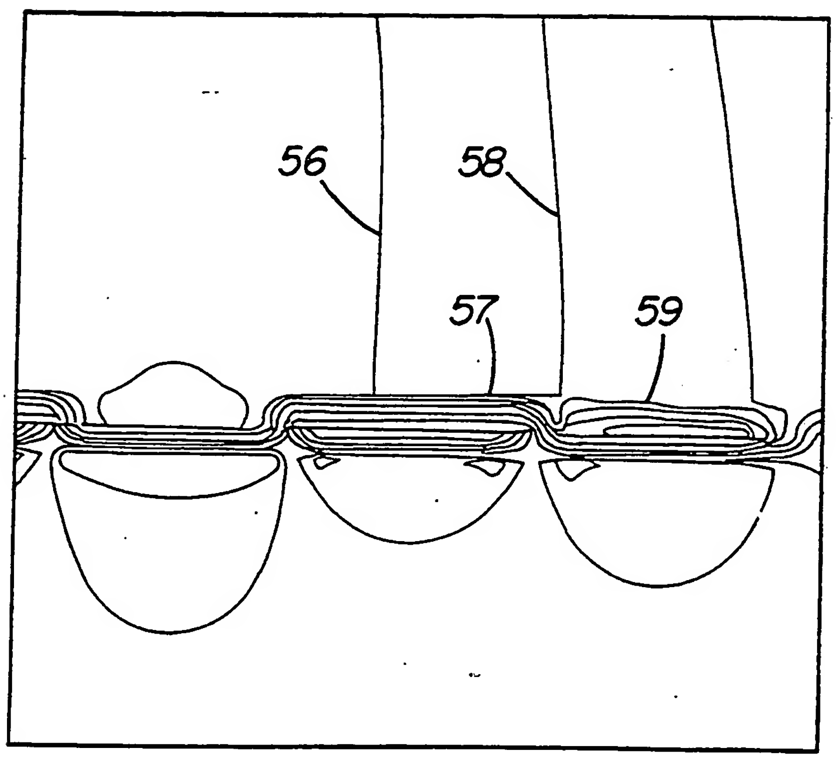


FIGURE 16B

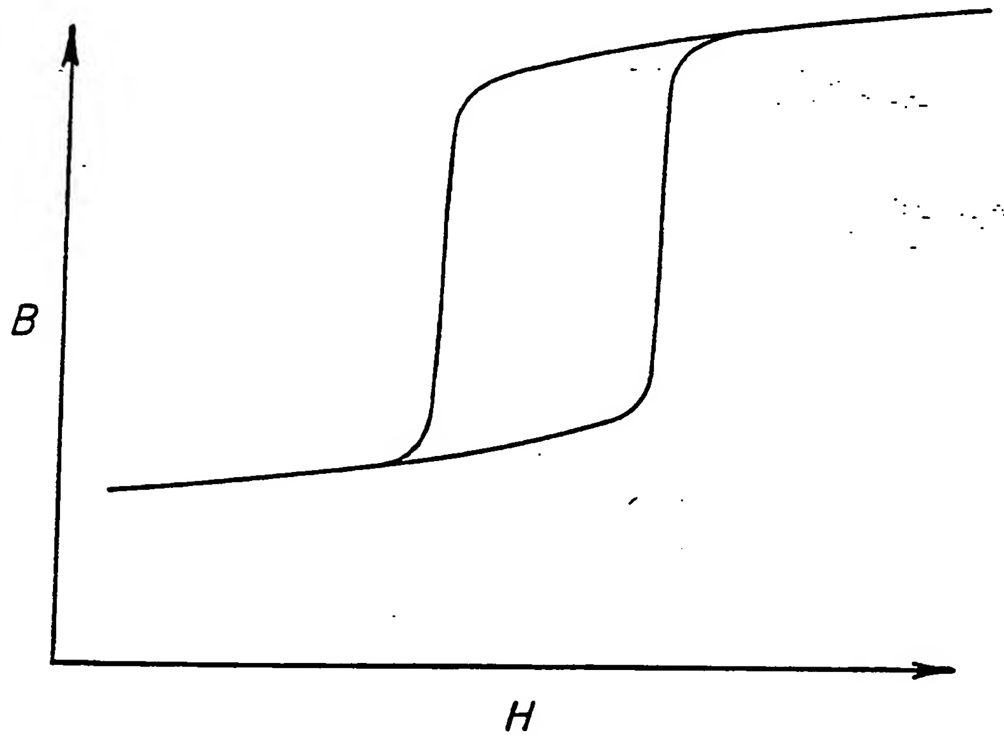


FIGURE 17 (PRIOR ART)

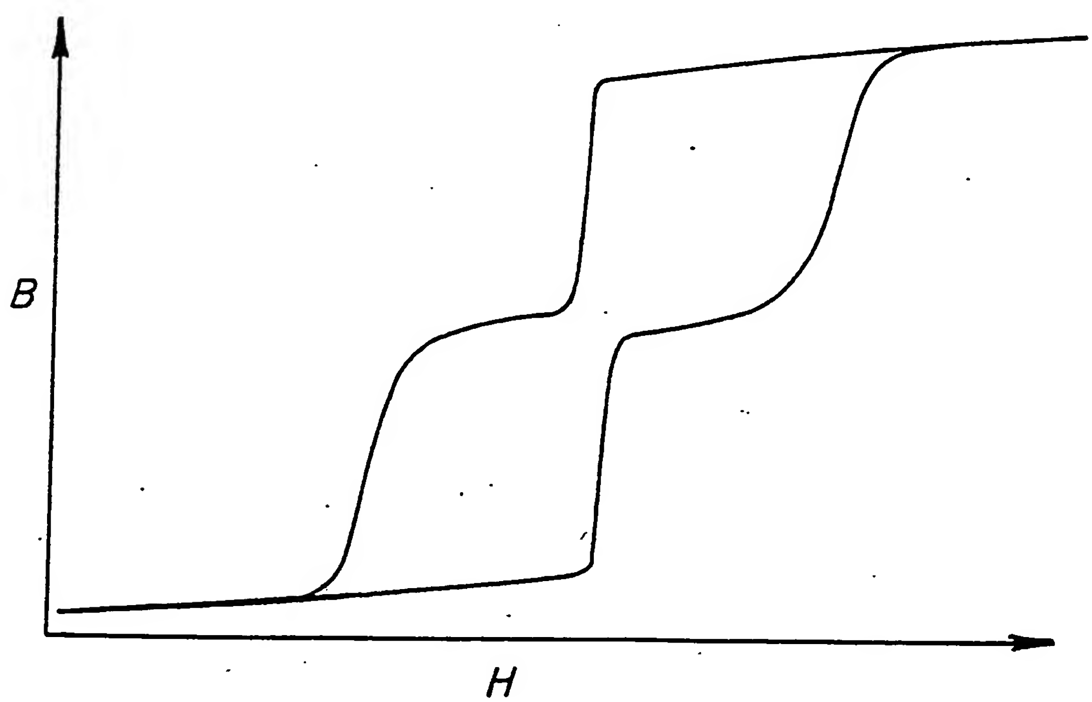


FIGURE 18

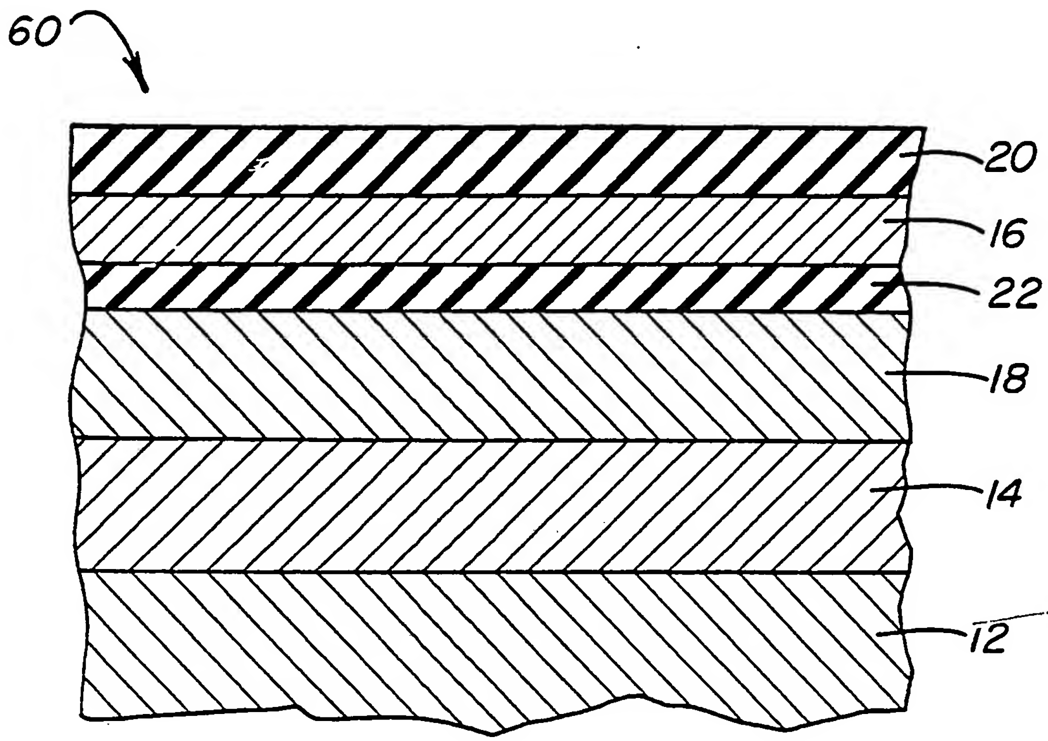


FIGURE 19

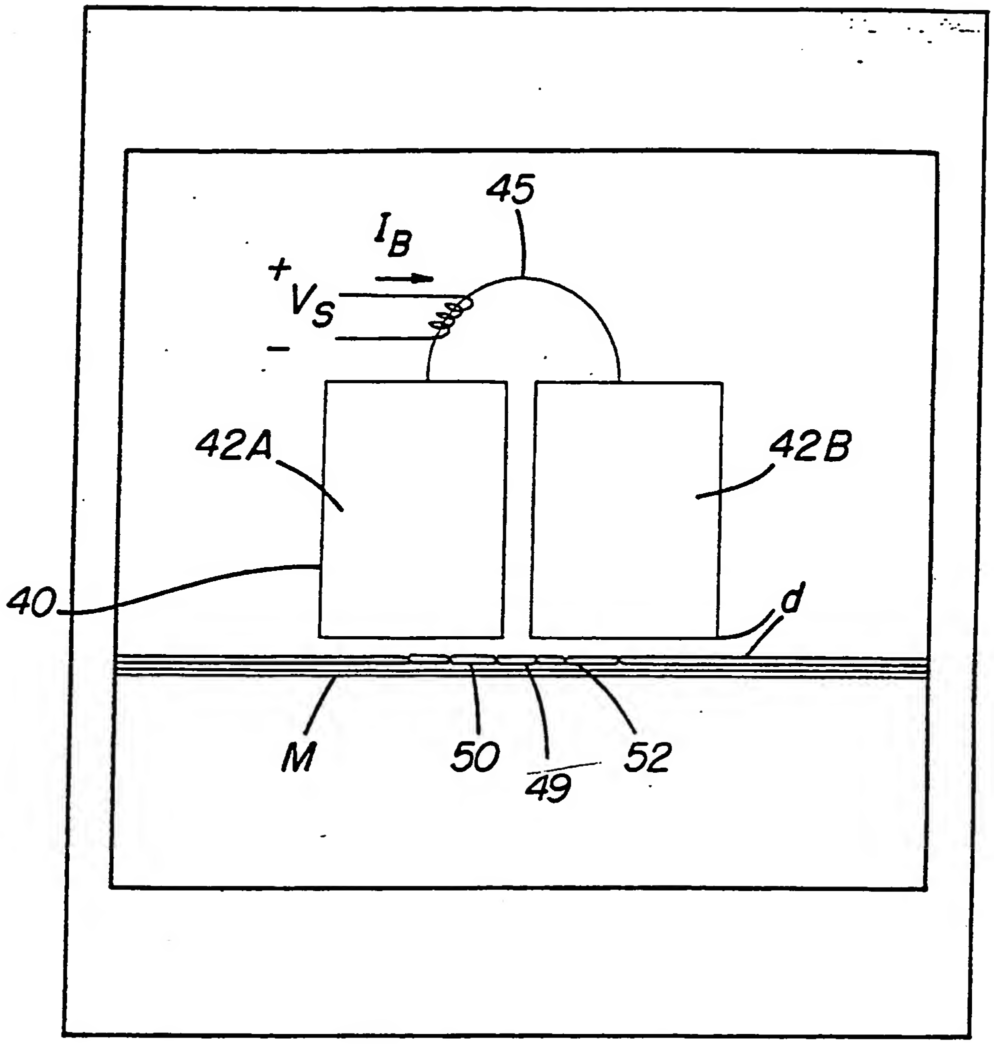


FIGURE 20

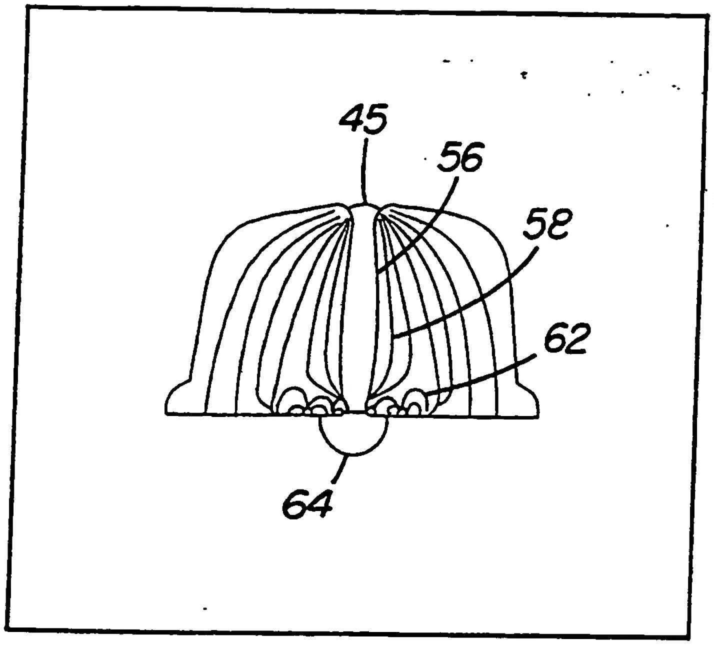


FIGURE 21A

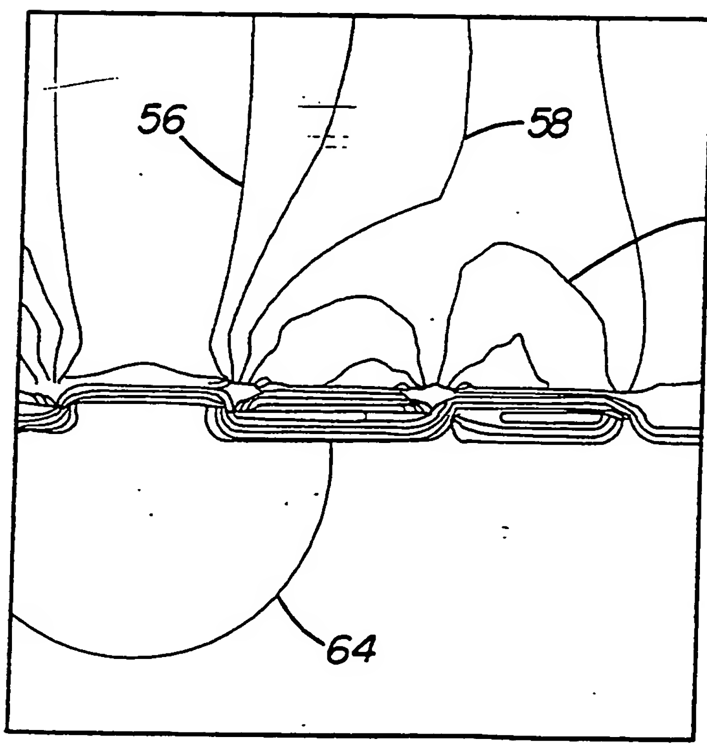


FIGURE 21 B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US92/10485

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :[redacted], 5/16, 9/00; H01F 1/00; G11B 5/66, 5/02
US CL :[redacted], 611, 694, 702; 204/192.1; 360/55
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 428/408, 446, 448, 450, 900, 928, 64, 336, 611, 694, 702; 204/192.1; 360/55

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US, A, 5,147,732 (SHIROISHI ET AL) 15 SEPTEMBER 1992; See Example 3, Figure 2.	1-27
Y	US, A, 3,677,843 (REISS) 18 JULY 1972; See Figure 1.	1-27
Y	US, A, 5,041,922 (WOOD ET AL) 20 AUGUST 1991; See Example 3.	1-27

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
28 JANUARY 1993

Date of mailing of the international search report
24 MAR 1993

Name and mailing address of the ISA/US
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Box PCT
Washington, D.C. 20231

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